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EVALUATION OF ARALL-4®: AN ARAMID FIBER REINFORCED ALUMINUM

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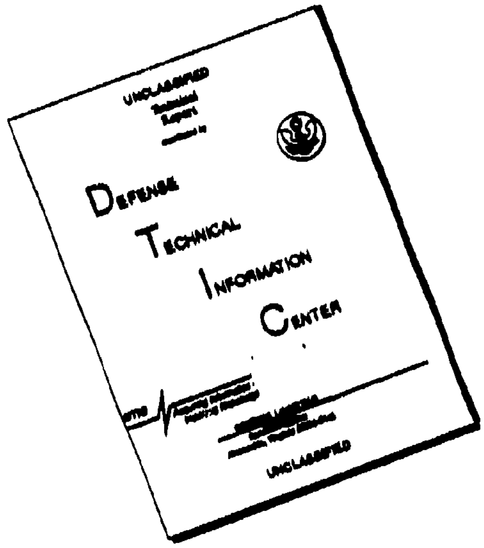

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ARALL-4® was evaluated for the following: tensile properties at elevated temperature; tensile properties in hot/wet conditions; moisture absorption; anisotropy and ballistic impact performance. The tensile properties of ARALL-4® exceed those of 2024-T8 in the longitudinal direction, but they are lower in the transverse direction. ARALL-4® retains excellent tensile properties after full saturation at 95% humidity and at 150°C. The moisture absorption of ARALL-4® is slow. The ballistic impact performance of ARALL-4® is inferior to several commonly used lightweight armor materials including: glass reinforced plastic, KEVLAR laminate, and titanium 6-4.

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INTRODUCTION

OBJECTIVE

The objective of this investigation was to evaluate the following properties of ARALL-4®: tensile properties at elevated temperature; tensile properties in hot/wet conditions; moisture absorption; anisotropy; and ballistic impact performance.

BACKGROUND

ARALL® is an ALCOA trademark which represents their line of metal/polymer reinforced laminates. This technology was developed at Delft University in the Netherlands during the 1970's. The first generation of these laminates was called ARALL®, (Aramid Aluminum Laminates). These laminates are comprised of high-strength aluminum sheets and unidirectional aramid fiber arrays impregnated with an adhesive. These layers are stacked, cured, and prestrained after curing. In collaboration with Delft University, Fokker aircraft, Enka and 3M Company, Alcoa began evaluation and manufacturing studies of ARALL® in 1983. In 1985, Alcoa began an extensive cooperative testing program to characterize ARALL® laminates [1]. The currently available ARALL® laminates include ARALL® 1 through 4. ARALL® 1 is made with 7475-T61 or 7075-T6 aluminum sheet and 3M's SP-366 prepreg. The prepreg is 50 wt% unidirectional aramid fibers in an AF-163-2 adhesive. ARALL® 2 and ARALL® 3 consist of 2024-T8 and 7475-T761, respectively, and the same prepreg system. ARALL® 4 is composed of 2024-T8 and a higher temperature prepreg, SP-376, which is made from AF-191 adhesive. The most attractive property verified in ALCOA's cooperative test program was the excellent fatigue resistance of these laminates compared to conventional aluminum alloys. Also, the ARALL® displayed a 15-20% lower density than conventional aluminum, a 60% higher longitudinal tensile strength than 7075 and 2024 aluminum, good resistance to fire and lightning strike, and good damping characteristics [2]. It was found that ARALL® laminates are more durable and less expensive than graphite epoxy composites. It has been estimated that these laminates would increase durability in fatigue prone areas with a potential weight savings of 30% with respect to aluminum due to higher design stress and lower specific weight [3].

The impetus for this study was to evaluate the material properties of ARALL-4® for use in a Naval environment. The properties evaluated include tensile properties at elevated temperature; tensile properties in hot/wet conditions; moisture absorption; anisotropic properties; and ballistic impact performance.

EXPERIMENTAL PROCEDURE

MATERIAL

The material was obtained from ALCOA in the form of 3/2 (3 aluminum layers/ 2 aramid prepreg layers) and 5/4 (5 aluminum layers/ 4 aramid prepreg layers) ply sheet material. The aluminum layers were 2024-T8; the prepreg layers were a unidirectional reinforced aramid fiber in a SP-376 resin system. Each aluminum layer was approximately .012 inches thick. The total thickness of the 3/2 ply was 0.054 inches. The total thickness of the 5/4 ply was 0.094 inches.

MECHANICAL PROPERTIES

The tensile tests were performed at the NAVAIRDEVCEN. A closed-loop MTS servo hydraulic test system was used. The tests were performed at a strain rate of approximately $3X10^{-4}$ in/in/sec. The tensile tests were performed according to ASTM standard B287. The longitudinal and transverse directions were evaluated. The tests were conducted at room temperature, both dry and after reaching full saturation at 95% humidity. Full saturation was defined as the point when no further weight gain was measured due to humidity exposure. Tests were also performed at 150° C, both dry and after reaching full saturation at 95% humidity. Additional tests were performed for off-axis orientations of 0, 30, 45, 60, and 90 degrees in the dry condition at room temperature.

MOISTURE ABSORPTION

Moisture absorption due to exposure at 95% humidity was measured. Flat tensile specimens, 9"long X0.625"wide, were exposed and tested. The percent weight gain versus time $^{1/2}$ was plotted. A linear relationship resulted. Therefore, the moisture absorption was characterized using Fick's first law. The two-dimensional diffusion equation for the laminates was derived in Reference 4:

$$\frac{\sqrt{D_l}}{l}+\frac{\sqrt{D_t}}{n}=\frac{\sqrt{\pi}}{4M_m}\cdot\frac{M}{\sqrt{t}}$$

D_l: diffusion coefficient in the fiber direction
D_t: diffusion coefficient perpendicular to the fiber direction
l: length of the specimen in the fiber direction
n: length of the specimen perpendicular to the fiber direction
M_m: maximum moisture content (%)
M: weight gain (%)
t: time

The parameters l, n, t, and M were obtained from the experimental data. The the ratio of diffusion coefficients D_l/D_t was calculated.

BALLISTIC IMPACT TESTS

Ballistic impact tests were performed at the Naval Research Laboratory (NRL) on the 5/4 ply material. The ARALL® sheets were subjected to low velocity, normal incidence impacts by .22 caliber projectiles. Tests were conducted using a rifled barrel chambered to take a HORNET case. Two different projectiles were used. A standard steel fragment projectile was used to enable comparison with previously tested materials. A soft lead CROSSMAN pellet was selected to examine the influence of hardness and nose configuration. The projectiles are shown in Figure 1. The velocities were measured immediately prior to impact using ballistic light screens and a 10 MHz counter. Velocities, which ranged from 587 m/s to 109 m/s, were obtained by varying the quantity of BULLSEYE or IMR-4064 powder. Impacts were spaced at least 75 mm apart in order to minimize the possibility of overlapping affected damage zones. The impact damage was examined optically and using an ultrasonic C-scan. The C-scans were performed at the NAVAIRDEVCEN. A limit velocity was calculated for each type of projectile. This velocity is defined in Tables 1 and 2.

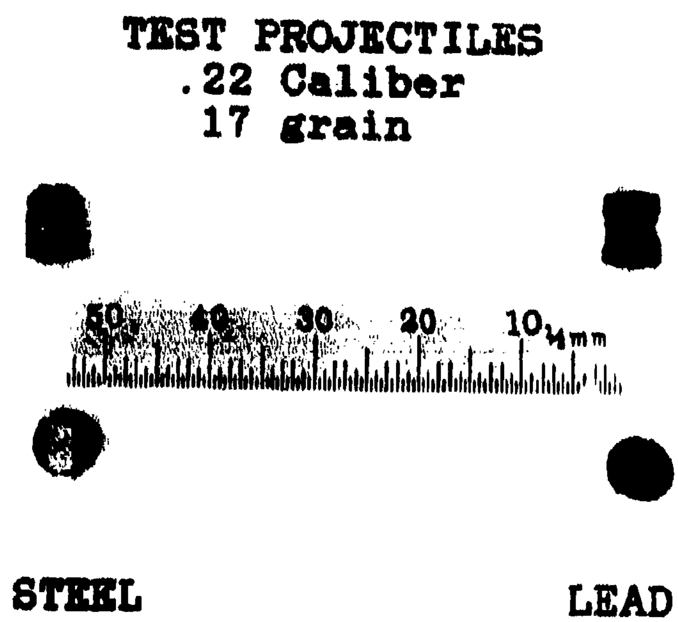


Figure 1. Projectiles used in Ballistic Evaluation of ARALL-4.

Tables 1. Results of Ballistic Impacts on ARALL-4® Sheet with Hard-Steel Projectile.

Material Identification 643664 - 1, 2, 3, 7
Thickness: ≈2.4 mm (.095 inch) Areal density: 17.5 oz./ft^2

Projectile: 17 grain Fragment Simulator - Steel - Hardness Rc 29
.22 Caliber - Army Type G-2

PENETRATIONS

Velocity	Front Deformation	Rear Deformation	"C"-Scan	Sheet ID
587 m/s	34 x 25 mm *	25 x 21 mm	32 x 24	643664-1
527 m/s	31 x 22 mm *	32 x 30 mm	31 x 34	-1
453 m/s	23 x 20 mm *	30 x 32 mm	30 x 37	-1
404 m/s	10 x 10 mm	26 x 19 mm	30 x 20	-1
302 m/s	12 x 10 mm	34 x 20 mm	37 x 25	-7
276 m/s	17 x 11 mm	37 x 25 mm	37 x 25	-7
244 m/s	23 x 13 mm	42 x 28 mm	42 x 29	-3
241 m/s	28 x 16 mm	43 x 27 mm	48 x 29	-2
240 m/s	28 x 15 mm	39 x 30 mm	49 x 30	-2
231 m/s	26 x 16 mm	42 x 29 mm	48 x 32	-2
203 m/s	22 x 14 mm	42 x 30 mm	51 x 30	-7

* Raised up

RETAINS

Velocity	Front Deformation	Rear Deformation	"C"-Scan	Sheet ID
182 m/s	33 x 21 mm	47 x 27 mm	54 x 29	643664-3
120 m/s	30 x 17 mm	32 x 24 mm	44 x 27	-2
109 m/s	28 x 17 mm	36 x 24 mm	36 x 24	-3

(C) indicates rear surface cracking in addtion to deformation

Limit velocity = V_L = (203 + 182)/2 = 193 m/s

Tables 2. Results of Ballistic Impacts on ARALL-4® Sheet with Soft-Lead Projectile.

Material Identification 643664 - 3, 4, 5, 6, 8
Thickness: ≈2.4 mm (.095 inch) Areal density: 17.5 oz./ft²

Projectile: 17 grain Pellet - Lead - Soft
.22 Caliber - Flat nose, hollow rear - CROSMAN ARMS

PENETRATIONS

Velocity	Front Deformation	Rear Deformation	"C"-Scan	Sheet ID
309 m/s	36 x 36 mm	57 x 36 mm	51 x 32	643664-5
291 m/s	48 x 31 mm	58 x 34 mm	52 x 36	-8

RETAINS

Velocity	Front Deformation	Rear Deformation	"C"-Scan	Sheet ID
268 m/s	58 x 34 mm	79 x 44 mm	76 x 27	643664-6
264 m/s	55 x 32 mm	69 x 40 mm (c)	66 x 27	-6
259 m/s	60 x 35 mm	66 x 41 mm (c)	77 x 40	-6
240 m/s	40 x 20 mm	48 x 28 mm	50 x 29	-3
237 m/s	50 x 38 mm	65 x 36 mm (c)	68 x 30	-5
232 m/s	53 x 30 mm	57 x 37 mm	66 x 34	-6
228 m/s	49 x 36 mm	70 x 38 mm (c)	70 x 36	-5
227 m/s	47 x 35 mm	52 x 38 mm (c)	63 x 33	-4
219 m/s	47 x 28 mm	53 x 37 mm	62 x 36	-4
194 m/s	40 x 30 mm	46 x 30 mm	46 x 27	-4
156 m/s	23 x 17 mm	35 x 27 mm	34 x 27	-4

(C) indicates rear surface cracking in addtion to deformation

Limit velocity + V_L = (291 + 268)/2 = 280 m/s

RESULTS AND DISCUSSION

MATERIAL

Transverse and longitudinal micrographs of ARALL-4® are shown in Figure 2. The grains are typical of rolled sheet. The grain size is 15μ X 32μ X 7μ, with the longest dimension in the rolling direction. The prepreg is well consolidated. There are no apparent voids, and the fibers are uniformly distributed.

MECHANICAL PROPERTIES

The tensile properties are shown in Figures 3 through 6. The following connotations were used: 3200 indicates a 3/2 ply sample at 0 degrees off axis. 3200T indicates tested at 150° C. 3200H indicates tested at room temperature after saturation from exposure to 95% humidity. 3200TH indicates tested at 150° C and saturated. Similarly, 5400 indicates a 5/4 ply sample at 0 degrees off axis, 3290 indicates a 3/2 ply sample at 90 degrees off axis, and 5490 indicates a 5/4 ply sample at 90 degrees off axis.

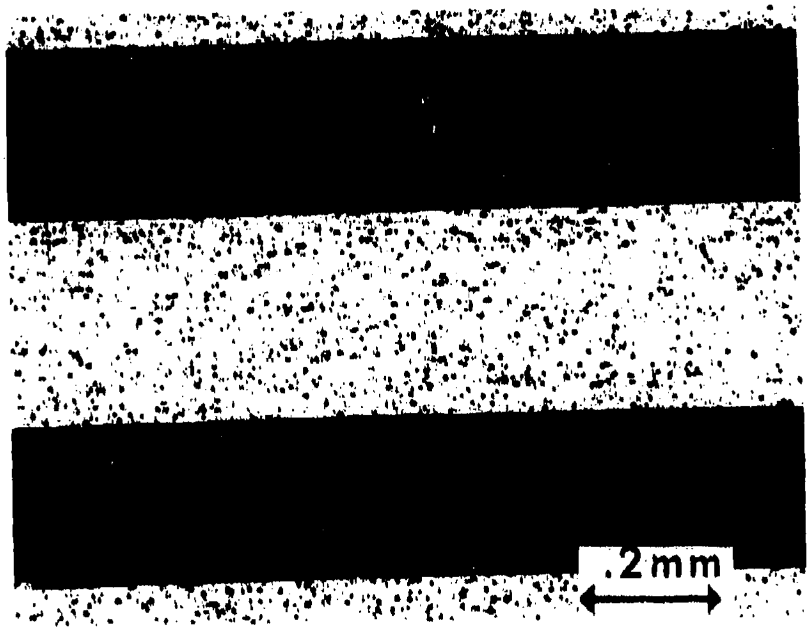
There were not significant differences in yield strength or tensile strength between 3/2 and 5/4 ply configurations (See Figures 3 and 5). This implies that the fabricating procedure is sufficiently optimized to make thicker laminates without a degradation in tensile properties. For both configurations, as expected, the highest yield strengths and tensile strengths were in the longitudinal direction due to the load carrying ability of the fibers. The longitudinal yield strength for the 3/2 and 5/4 ply configurations were 447 and 414 MPa, respectively (See Figures 3 and 5). The transverse yield strengths for the 3/2 and 5/4 ply configurations were approximately 32% and 29% lower than that of the longitudinal (See Figures 3,4,5, and 6).

The strength properties at 150° C were slightly lower in both the transverse and longitudinal directions than those at room temperature. The transverse yield strength at 150° C was 55-46 MPa (8-7 ksi) lower. The longitudinal yield strength at 150° C was 37-24 MPa (5-3 ksi) lower. The fiber reinforcement makes a significant contribution to the yield strength in the longitudinal direction. However, it does not contribute to the yield strength in the transverse direction. The yield strength in the transverse direction relies on contributions from the resin and aluminum layers. Therefore, the yield strength data indicate that high temperature has more of a detrimental effect on the resin system than on the load bearing fibers. The longitudinal yield strength of ARALL-4® at 150° C is 2% greater than that of 2024-T8 at room temperature.

Ninety-five percent humidity exposure did not degrade the strength properties at room temperature. This supports the hypothesis that the aluminum sheets act as barriers to moisture absorption[4,5], and hence, excellent properties were exhibited after exposure to 95% humidity. The 3/2 ply longitudinal yield strength only decreased slightly. The 5/4 ply longitudinal yield strength remained the same within the limits of statistical variation.

The combined effects of supersaturation from humidity exposure and elevated temperature caused a slight decrease in properties. In all cases the yield strengths were 10 MPa less than the dry samples tested at elevated temperature (150° C), except the 5/4 transverse sample which exhibited the same yield strength. Therefore, the humidity exposure did not degrade the tensile properties significantly at elevated temperatures.

a)



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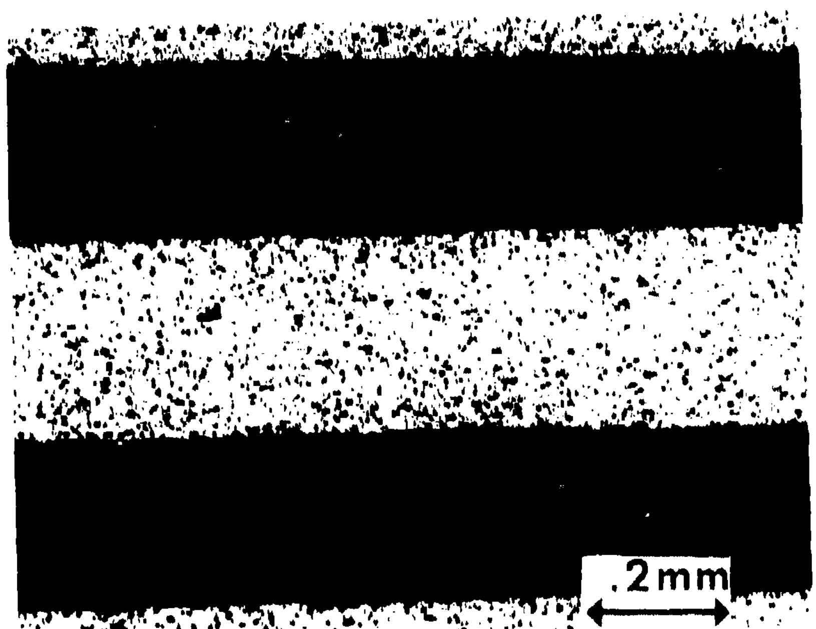


Figure 2. ARALL-4® 3/2 ply, Optical Micrographs
a) Transverse
b) Longitudinal

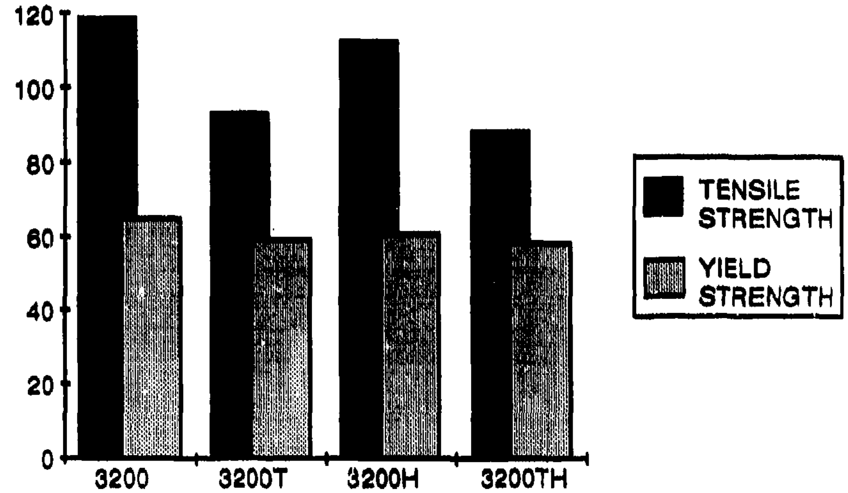


Figure 3. Tensile Properties ARALL-4® 3/2 Ply, Longitudinal. 3200 - Room Temperature, 3200T -150° C, 3200H - Saturated at 95% Humidity, 3200TH - 150° C and Saturated at 95% Humidity.

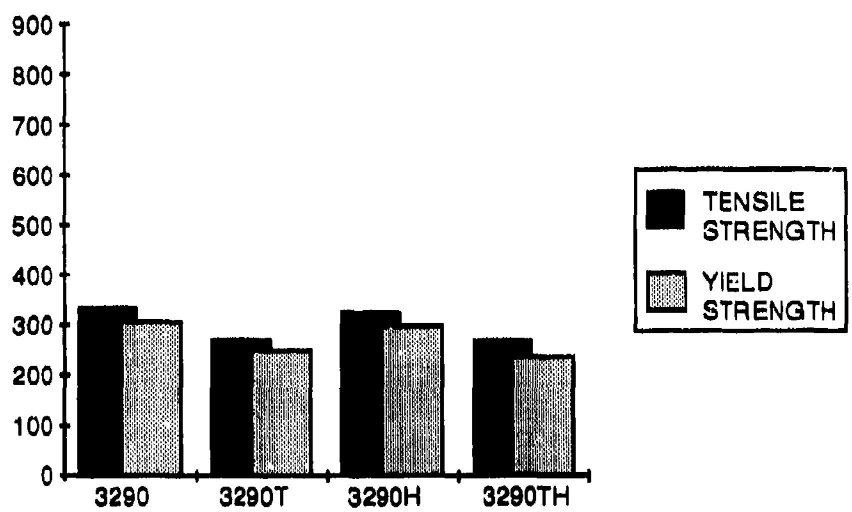


Figure 4. Tensile Properties ARALL-4® 3/2 Ply, Transverse. 3290 - Room Temperature, 3290T - 150° C, 3200H - Saturated at 95% Humidity, 3200TH - 150° C and Saturated at 95% Humidity.

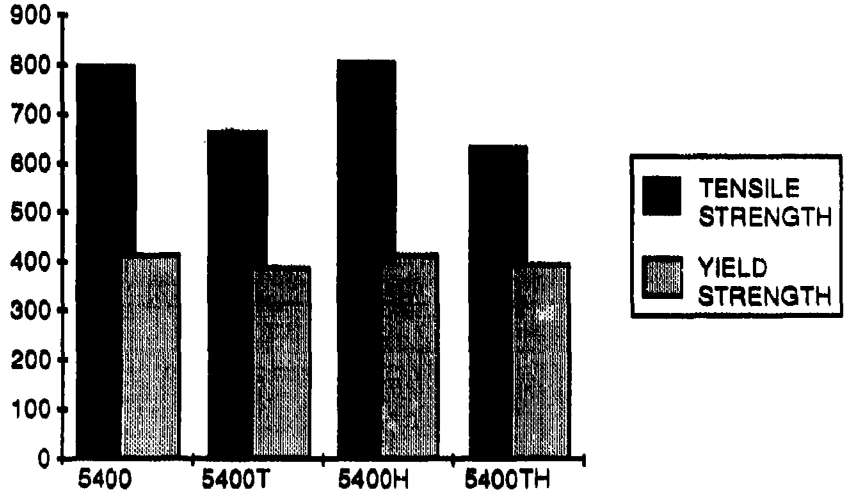


Figure 5. Tensile Properties ARALL-4® 5/4 Ply, Longitudinal. 5400 - Room Temperature, 5400T -150° C, 5400H - Saturated at 95% Humidity, 5400TH -150° C and Saturated at 95% Humidity.

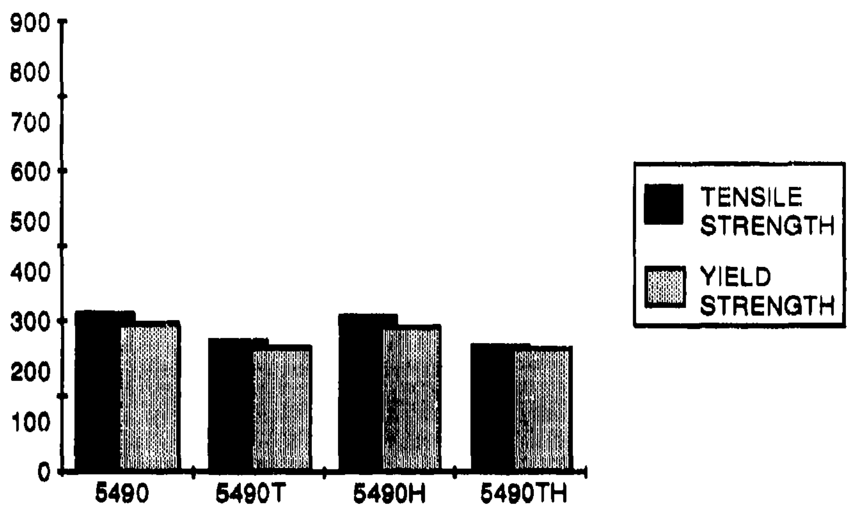


Figure 6. Tensile Properties ARALL-4® 5/4 Ply, Transverse. 5490 - Room Temperature, 5490T - 150° C, 5490H - Saturated at 95% Humidity, 5490TH - 150° C and Saturated at 95% Humidity.

The hot/wet performance of ARALL-4® is superior to the hot/wet performance of unidirectional AS-3501 graphite/epoxy composites, designated GR90TH, (See Figure 7a). The ARALL® aluminum layers impart transverse strength, and they also act as barriers to moisture absorption. However, unidirectional ARALL-4® does not compare well with conventionally used crossply graphite epoxy composites, designated GR(I). The transverse hot/wet performance of ARALL-4® is lower than that of isotropic AS-3501 graphite epoxy, designated GR(I)TH, (See Figure 7b). This is due to the unidirectional reinforcement of the ARALL-4®. A crossply version of ARALL would be more competitive with isotropic graphite epoxy.

Moduli were measured for several of the ARALL® configurations (See Figure 8). As expected the moduli were higher for the longitudinal direction in both the 3/2 and 5/4 ply laminates. This is due to the unidirectional fiber orientation.

The off-axis tensile data is shown in Figure 9. As expected the highest strength values are in the longitudinal direction. The properties decrease as the testing direction changes. Both the yield strength and the ultimate tensile strength exhibit their lowest values in the transverse directions. This trend also holds true at 150 °C. Although ARALL® has unidirectional reinforcement, the anisotropic behavior is mitigated by the presence of the aluminum layers. However, the lower transverse properties of unidirectional ARALL® laminates may limit the applications for this material. Note from Figure 9, the yield strength of ARALL-4® is consistently lower than that of 2024-T8 sheet for all the off-axis orientations. Tensile strength criteria alone do not warrant the use of ARALL laminates. Other criteria, such as fatigue performance, are necessary drivers for the implementation of ARALL® laminates.

MOISTURE ABSORPTION

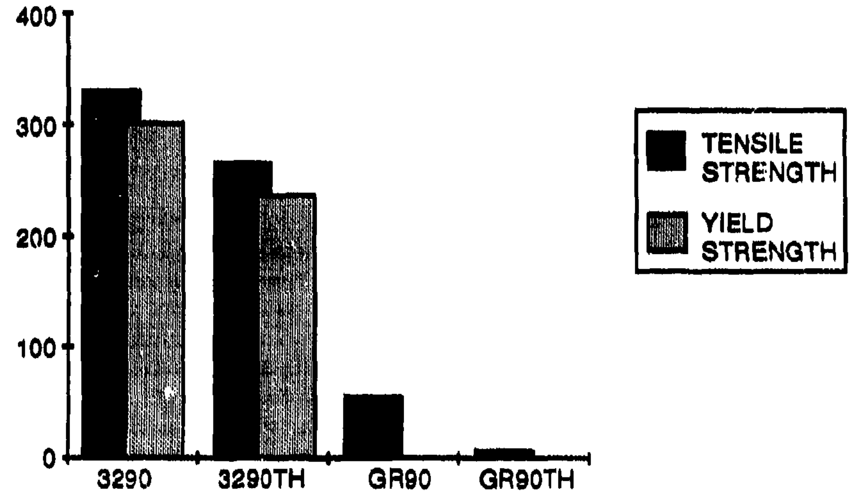
A plot of the percent weight gain versus time$^{1/2}$ is shown in Figure 10. The weight did not increase after approximately 20 days exposure at 95% humidity. The data in Figure 10 is representative of transverse and longitudinal samples of 3/2 ply ARALL-4® which were exposed to 95% relative humidity at room temperature. The plots show a linear relationship and, therefore, can be interpreted using equations derived from Fick's first law. The ratio of diffusion coefficients, D_l/D_t, was calculated to be approximately 4.0. This is slightly lower than the values published for ARALL-1® and ARALL-2®, 4.7. [5]. It is clearly shown that the diffusion of moisture in the fiber direction is higher than perpendicular to the fiber direction. This agrees well with the experimental observation that for a given time period the weight gain is higher for the transverse specimens.

BALLISTIC IMPACT TESTS

A summary of the ballistic impact results from the steel fragment simulator are shown in Table 1. The limit velocity was between 182 m/s and 203 m/s. This is low in comparison with other homogeneous and laminated materials [6]. 2024 aluminum has a similar limit velocity. 5083 aluminum, DORON GRP, NYLON laminate, Hadfield steel, KEVLAR laminate and titanium 6-4 all exhibit substantially higher limit velocities [6].

Results from the lead pellet tests are given in Table 2. The limit velocity using the lead pellet was between 268 and 291 m/s. As expected, the limit velocity for the lead pellet was higher than the limit velocity for the steel pellets. The energy required for the soft lead pellet to penetrate the ARALL-4® sheet was approximately twice that needed for the steel fragment simulator to penetrate.

a)



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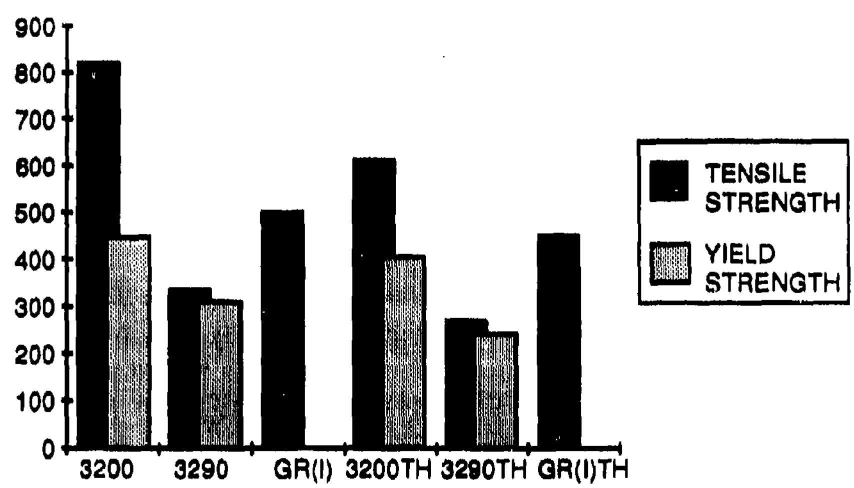


Figure 7. Hot/Wet Data @ 150° C and Saturated at 95% Humidity.
a) ARALL-4® 3/2 Ply, Transverse Tensile Properties. 3290 - ARALL-4® Room Temperature, 3290TH - ARALL-4® at 150° C and Saturated at 95% Humidity. GR90 - AS3501 Unidirectional Graphite Epoxy, Room Temperature. GR90TH - AS3051, 150° C and Saturated at 95% Humidity.
b) ARALL-4® 3/2 Ply, Transverse & Unidirectional AS3501 Graphite/Epoxy, Transverse 3/2 Ply, Isotopic Graphite/Epoxy AS3501. 3200 - ARALL-4® 3/2 Ply, Longitudinal, Room Temperature. 3290 - ARALL-4® 3/2 Ply, Transverse, Room Temperature. GR (I) - AS3501, Crossply 45° - 90° - 45° TH - at 150° C and Saturated at 95% Humidity.

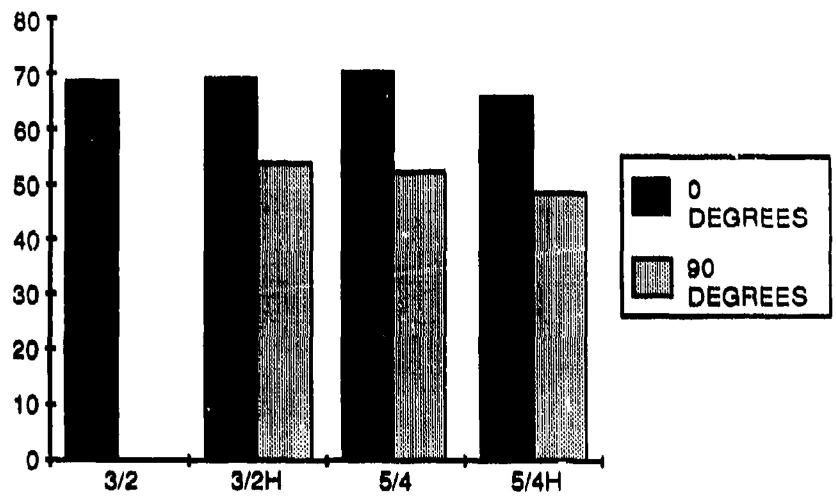


Figure 8. Young's Modulus, Longitudinal and Transverse, 3/2 Ply and 5/4 Ply, 3/2H and 5/4H - Saturated @ 95% Humidity.

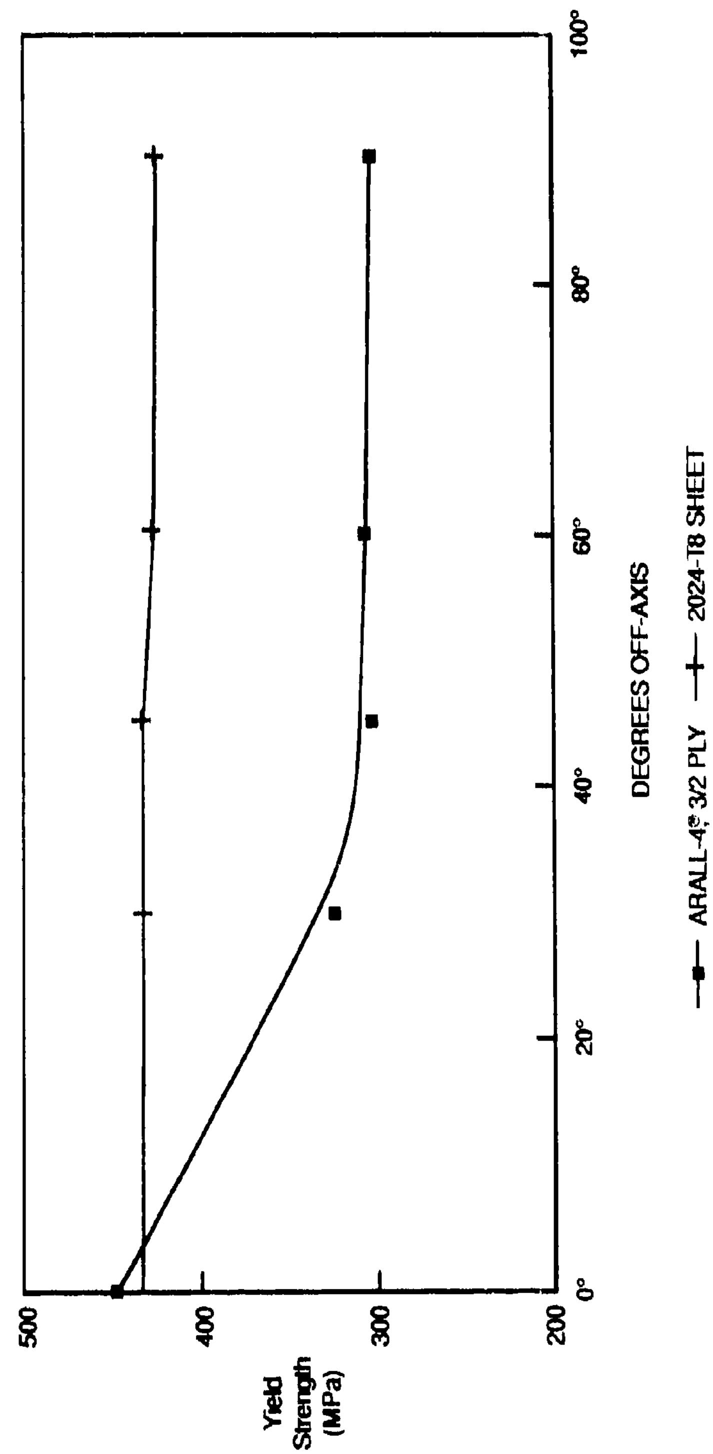


Figure 9. Off-Axis Yield Strength, ARALL-4®, 3/2 Ply and 2024-T8.

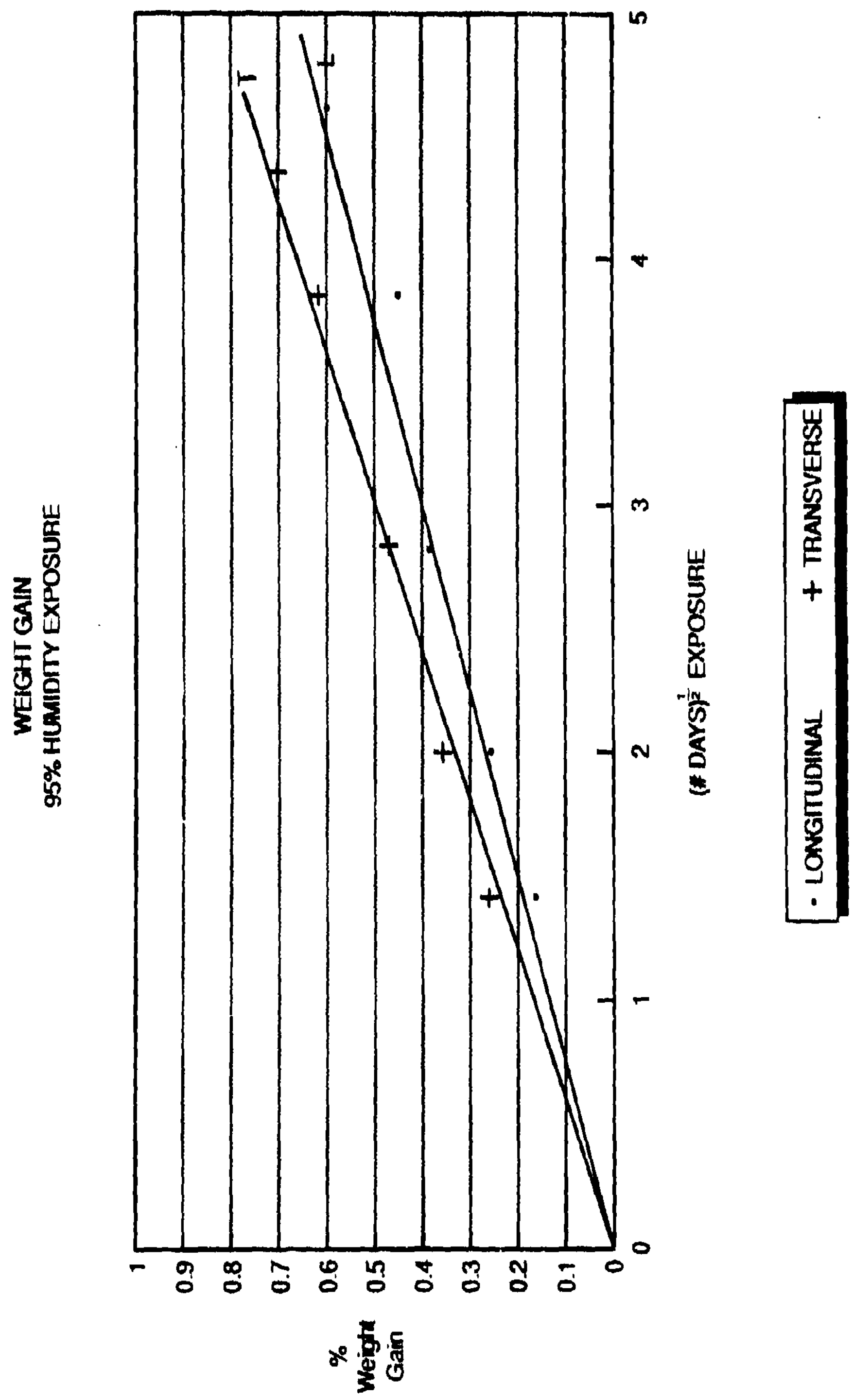


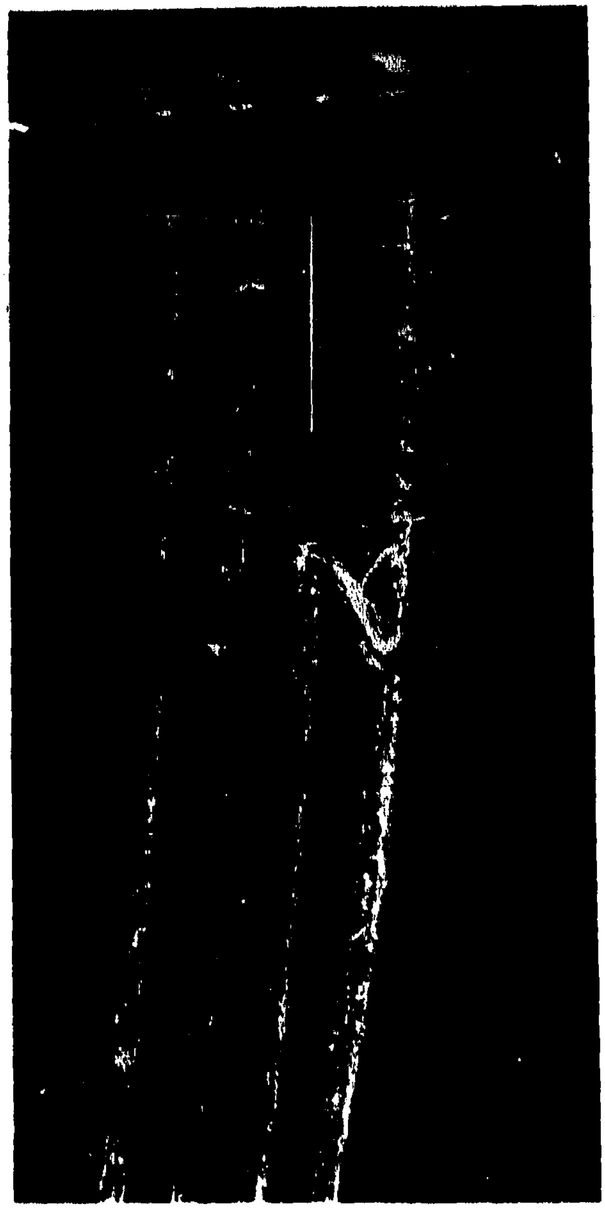
Figure 10. ARALL-4, 3/2 Ply, Moisture Absorption at 95% Humidity Versus Time.

The impacts of both the steel and lead projectiles resulted in deformation elongated in the longitudinal direction of the sheet. Typically, the rear deformation was greater than the front deformation. This indicates an internal rearrangement of the laminate constituents in the volume near the impact. The C-scan measurements, which reveal cracking and delamination, detected an affected area that matched or exceeded the optically determined limits of deformation. Examination of a 1.5-mm wide section along the long axis of a crater, produced by a nonpenetrating impact, revealed that each aramid layer contained cracks/delaminations extended to the limits of the optically detected deformation. These cracks/delaminations corresponded to the limit of affected area indicated by the C-scan. A portion of the section containing the delamination is shown in Figure 11.

The records of C-scan measurements of impacts with both lead and steel projectiles are shown in Figures 12, 13, and 14 for impacts well above the limit velocity, near the limit velocity, and below the limit velocity, respectively. The elongation of the affected region is noticeable for each condition. The affected area is many times larger than the 5.6 mm diameter circular area of the impacting projectile. An indication of nonuniformity in the laminate sheet is provided by the C-scan records in Figure 15. These are records of impacts made with the lead pellet at 228 m/s (top photo) and 232 m/s (bottom photo), both well below the limit velocity. The affected area from the 228 m/s impact is longer and wider than that from the 232 m/s impact. In addition, a long crack formed on the 228 m/s velocity impact while no crack formed on the 232 m/s velocity impact. These shots are from different sheets. This behavior may represent sheet to sheet variation.

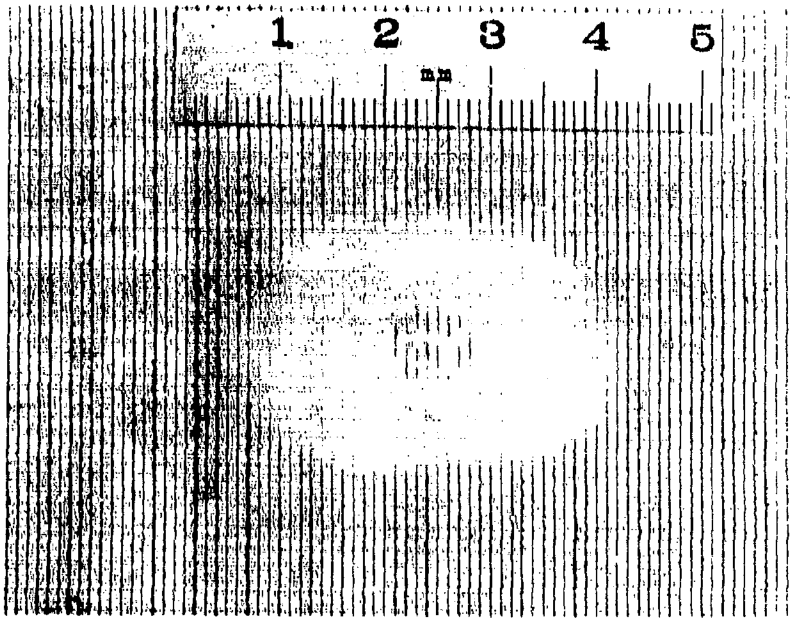
Another difference in impact response to the steel and lead projectiles is illustrated in the photographs shown in Figure 16. The cracking on the rear surface of the laminates typically consisted of three cracks at approximately 120° intervals for impacts made with the steel projectile. For impacts made with the lead pellet, however, a single crack formed parallel to the long dimension of the sheet.

The impact testing of ARALL-4® reported here indicates that the material is relatively ineffective as a lightweight armor. The limit velocity determined with the .22 caliber steel fragment simulator is low when compared to commonly used lightweight armors [6]. Extensive deformation and delamination results from impacts with projectile velocities well below to well above the limit velocity. Significant differences are apparent in response to impact by hard versus soft projectiles.

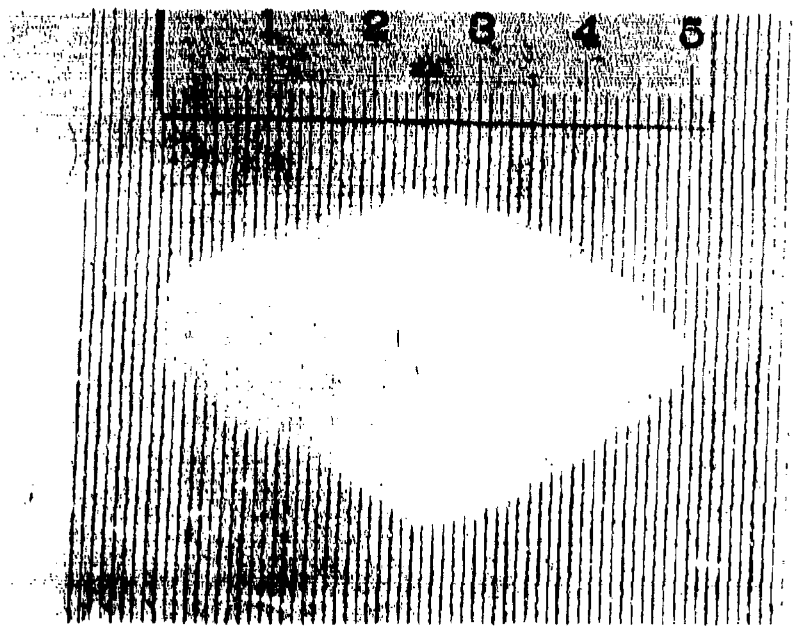


IMPACT SIDE OF TARGET

Figure 11. Thin Section through Midline of Nonpenetrating Impact with Lead Pellet, Showing Cracks in Aramid Layers.

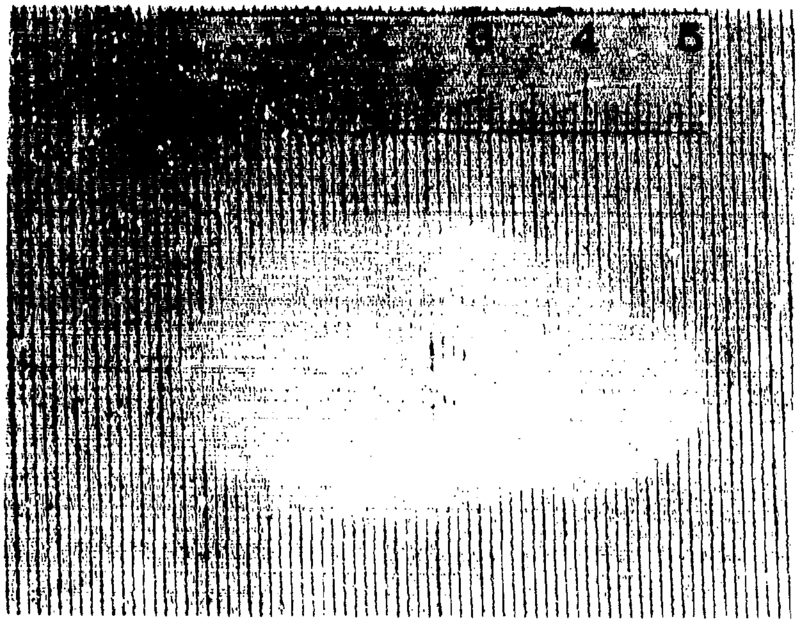


Projectile: .22 cal. steel Velocity: 302 m/s

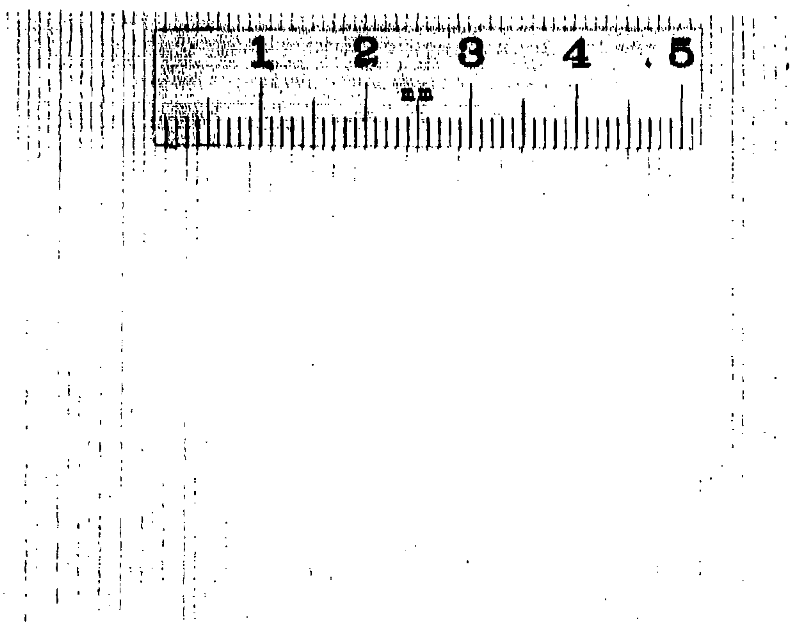


Projectile: .22 cal. lead Velocity: 309 m/s

Figure 12. C-scan Records of Impacts which Penetrated ARALL-4
(Well Above the Limit Velocity).

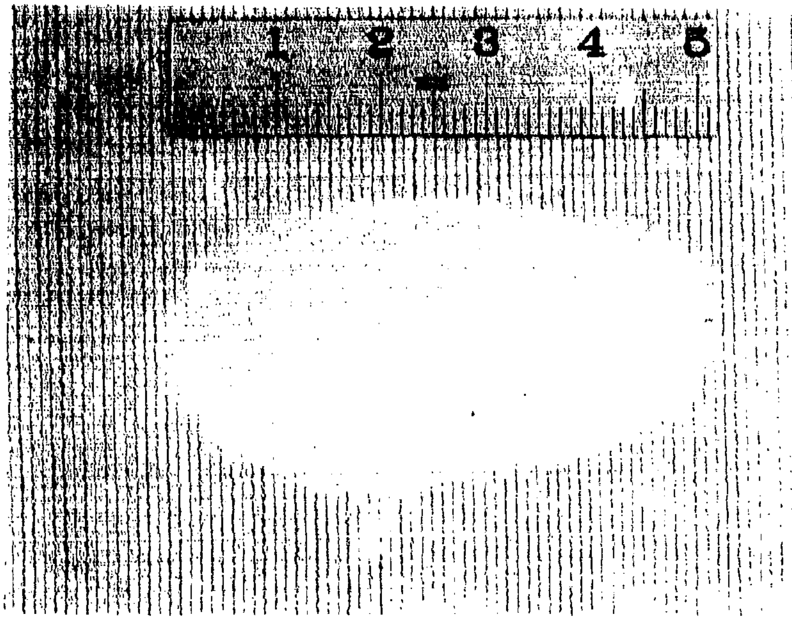


Projectile: .22 cal. steel Velocity: 203 m/s

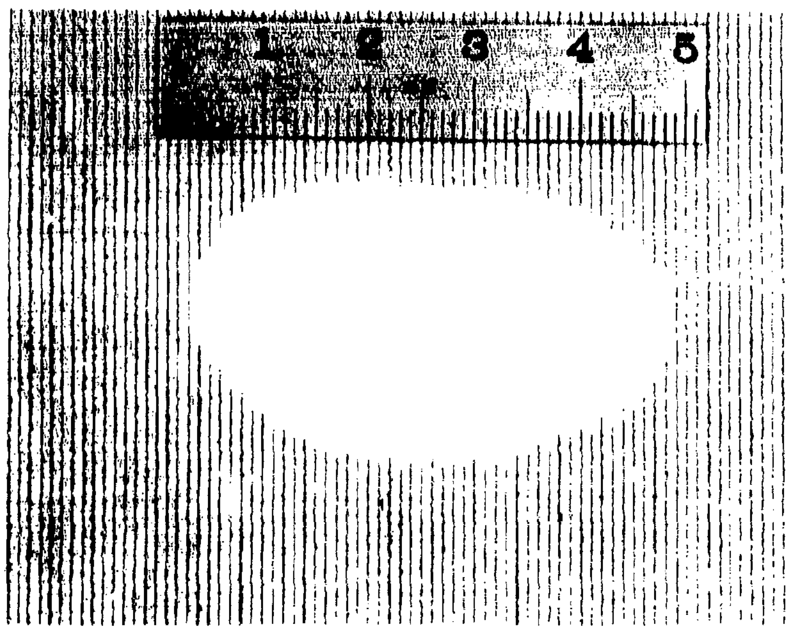


Projectile: .22 cal. lead Velocity: 291 m/s

Figure 13. C-scan Records of Impacts with Lowest Penetration Velocity for ARALL-4® (Near the Limit Velocity).

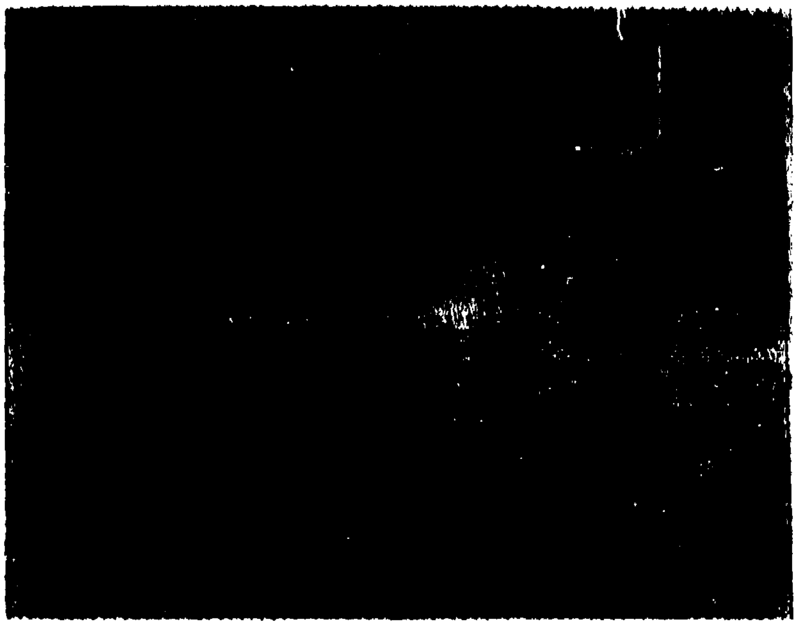


Projectile: .22 cal. steel Velocity: 182 m/s

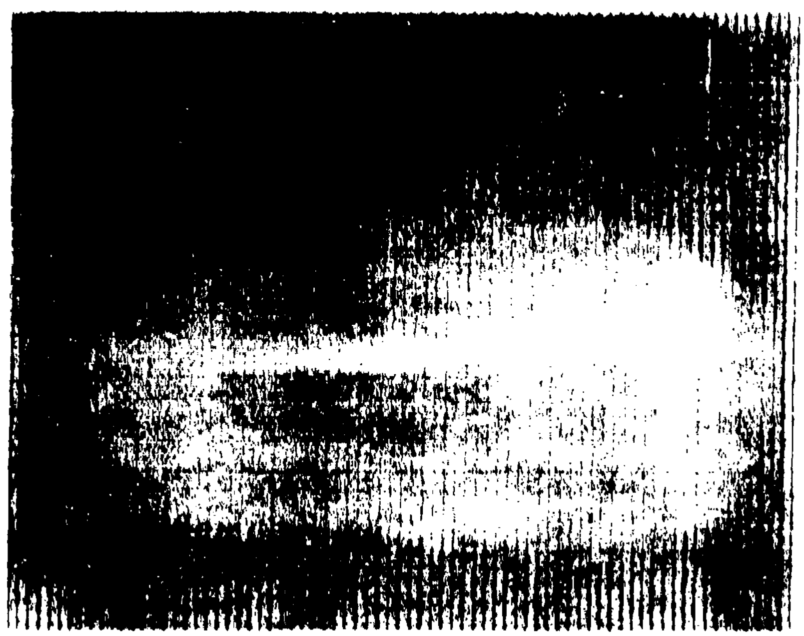


Projectile: .22 cal. lead Velocity: 194 m/s

Figure 14. C-scan Records of Impacts Which did not Penetrate ARALL-4® (Below the Limit Velocity).

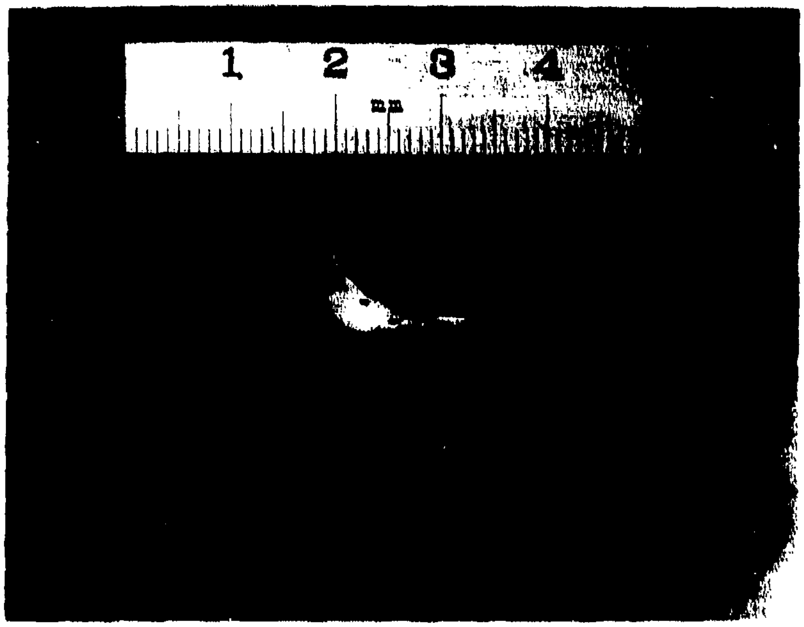


Projectile: .22 cal. lead Velocity: 228 m/s

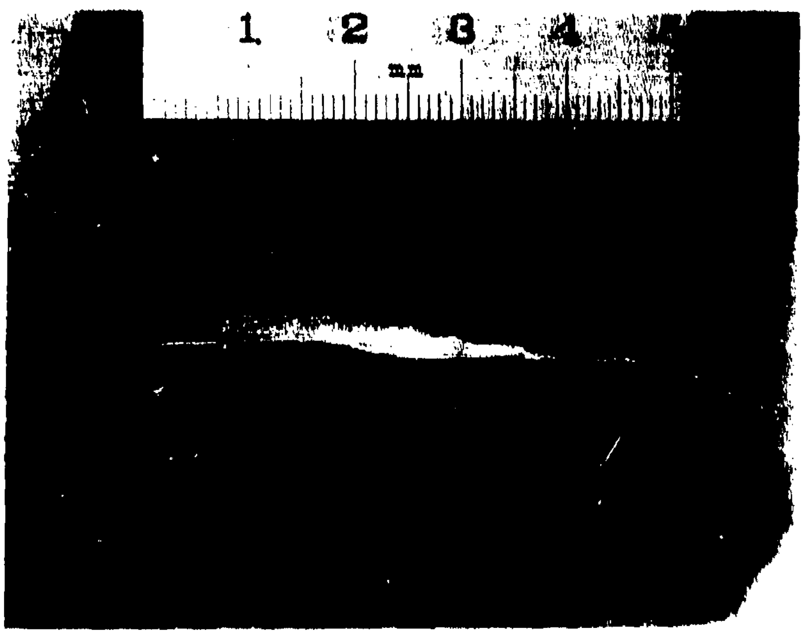


Projectile: .22 cal. lead Velocity: 232 m/s

Figure 15. C-scan Records of Nonpenetrating Impacts of ARALL-4® at Similar Velocity, Showing Different Affected Areas.



Projectile: .22 cal. steel Velocity: 182 m/s



Projectile: .22 cal. lead Velocity: 268 m/s

Figure 16. Rear Surface Cracks on ARALL-4® for Nonpenetrating Impacts.

CONCLUSIONS

1. ARALL-4® displays tensile properties in the longitudinal direction which exceed that of 2024-T8 sheet. However, the off-axis tensile properties are lower.

2. ARALL-4® retains excellent tensile properties in the completely saturated condition upon exposure to 95% humidity.

3. At elevated temperatures (150° C) ARALL-4® exhibits a slight drop off in tensile properties. In addition, this drop off in tensile properties is similar at 150° C in the fully saturated condition. This confirms the low moisture absorption of ARALL-4® laminates.

4. The Hot/Wet tensile properties of ARALL-4® are competitive with graphite/epoxy composites.

5. ARALL-4® laminates exhibited a linear relationship between moisture absorption and time$^{1/2}$. The diffusion coefficient of moisture in the fiber direction was 4.0 times greater than that perpendicular to the fiber direction.

6. ARALL-4® exhibits ballistic impact resistance comparable to 2024-T6. However, the impact resistance is inferior to several materials including KEVLAR laminate, glass-reinforced plastic, and titanium 6-4.

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